Contamination and Materials Risk Management in Solid State Laser Systems

John S. Canham, Ph.D.
Swales Aerospace, Inc.
5050 Powder Mill Rd.
Beltsville, MD 20705
jcanham@swales.com
voice: 301-286-8970

Contamination and materials degradation are among the highest risks associated with the deployment of high intensity solid-state laser systems. Although high intensity laser induced optical damage has been studied for decades, the field is still in its infancy. There is little concrete information concerning the relationship of contamination and laser induced optical damage. Further, little information exists in the measurement and evaluation of contamination at the levels of significance for high intensity solid-state lasers. The interconnection of the physical sciences in the area of laser induced optical damages disjointed at best. As a result, much of the information concerning the risk of contamination induced laser optical damage is conjecture. A number of valuable insights with respect to the potential problems, potential solutions and the mechanisms behind contamination induced laser optic damage are presented.

Introduction:

For the purposes of this discussion, there are two typical categories of lasers sealed and vented. These two types of laser environments each present their own issues with respect to contamination and materials reliability. The selection of materials and processes for each type of system is in part dependent upon the type of the laser system in use. There will be trade-offs between material performance properties, molecular contamination and particulate contamination. There is not a single material that will provide the best properties for all configurations and all projects. Selection of the best material for each application requires the balancing of the performance requirements for each material in an appropriately weighted manner. Identifying the reasoning for the material selection is important for future applications.

Environmental effects:

The determination of the operation and deployment environment of the laser system plays a significant role in the determination of the appropriate initial screening of the materials for the application. The operation of high intensity laser systems in a laser laboratory, on-board an aircraft, or on a spacecraft represent vastly different environments. Therefore, there are a number of different materials and contamination issues to be dealt with in these environments.

In a laser laboratory, one can typically take many fewer precautions with respect to the the issues of materials behavior and contamination. In this environment, there are a number of factors in operation that mitigate materials degradation issues, and contamination related laser optic damage. There are likely differences between the operational service environments of the field use laser and the laboratory laser that are not known, that differentiate the behavior of lasers. These include the dilution effects of the atmosphere, the limitation of the transport due to gravity and the mean free path within the pressure regime. Particles that deposit on surfaces of the laser, with the exception of the optics, will tend to remain in place. The laboratory presents very little thermal challenge to the laser as well. The potential for identifying and abating contamination and materials risks during operation minimizes risk for total laser loss. In the event of damage, the laboratory laser can be quickly shut down and the optic replaced prior to significant damage propagation. The laboratory environment presents the lowest risk damage environment.

Aircraft based lasers present a slightly higher risk environment. In these cases, there will typically be thermal changes that will result in the migration of molecular contaminants and in differential expansion that can result in contraction and stress on the optic. There will be acceleration, deceleration and vibrational forces that will result in the redistribution of particles within the laser system. In these systems, the risk of contamination and materials behavior is significantly higher than that which will typically be seen in the laboratory. Aircraft based laser systems may operate either in a sealed or vented environment. In a vented system, the laser may vary between atmospheric pressure to low vacuum. With the exception of inert gas purged sealed systems, the system will be primarily in an oxidative environment. Sealed laser systems build up contamination in the gas phase and redistribute the contaminants based upon the thermal and excitational properties of the surfaces in the laser. Airborne lasers still provide the opportunity for repair and replacement of damaged optics upon return to the ground.

Space based lasers represent a significantly higher risk environment. Space borne lasers may either be sealed or vented. In the case of sealed lasers, the risk of damage is not unlike the risk to airborne lasers, with the exceptions of radiation, operational lifetime and repair. If proper treatment of the potential radiation effects has been taken care of, sealed space based lasers can be treated similarly to airborne laser systems. Vented space borne lasers systems are dynamic environments. Upon initial venting, the gas phase material will be purged. This is followed by the gradual loss of adsorbed water from the interior of the laser. Gradually, the environment within the laser will become less oxidative, and more reductive due to the loss rate of water versus the loss rate of contaminants. This will significantly change the behavior of the contaminants in the laser system.

Materials Behavior:

The behavior of matter is canonical. Matter under a given set of conditions will behave in the same way. If under apparently identical conditions, a different behavior is seen, some other property of the system is not being taken into account. Anomalous behavior is only anomalous because its mechanism has not been identified. Only by identifying the fundamental rules defining the behavior of matter and high intensity radiation at the atomistic level it is possible to predict the behavior of matter and radiation under any conditions. The primary issue is the identification and validation of the assumptions in the description of the system. There is no stochastic behavior, only under-defined systems.

The interaction of matter with other matter is often over simplified. The interactions of matter are primarily controlled by the electronic molecular orbital interactions. These orbital interactions are primarily described by the multipole interactions between the static and induced multipoles. The multipole interactions are highly directional, inherently non-linear, and vary significantly over distances measured in fractions of a nanometer. A typical high energy surface will have a surface field measured near the immediate surface, will have a field equivalent to billions of volts per meter.[1] The presence of other materials on the surface will change the behavior of the surfaces significantly. The properties of the surface will be highly dependent upon the type and amount of the material on the surface.

The high surface energy of metals is typically reduced by surface oxides and/or surface adsorbed materials. The same is true of oxide surfaces. Surface fields are sufficiently large to change the chemical behavior of surfaces significantly over bulk behavior. Platinum is known to not form bulk oxides, but platinum exists with surface oxides, that will re-form if removed. As a gross estimate the energy of a surface is roughly equivalent to the tensile strength of the material at 0 K.[2] Adamson states that this is probably an under estimates the surface energy.

Surfaces under normal terrestrial conditions will be covered with a number of molecular layers of water, typically on the order of ten to fifty. The properties of this water are significantly different than that of bulk water, due to the field gradient in which it exists. The last few mono-layers are sufficiently tightly bound that they will remain within vacuum systems for estimated thousands of years at room temperature, even if exposed to an "absolute vacuum." Application of sufficient energy in the form of light, heat or other radiation can dislodge the water from the surface more rapidly. Typically weeks of heating at 250 ºC is required to deplete the vacuum system of water. This effect is partly due to reaction of the water, and partly due to desorption.

Molecular contamination adsorbed to a pristine surface is retained by the multipole interactions at the surface. These electronic interactions necessarily must follow the interaction behavior of molecular orbitals. The orbitals of the "surface" and the orbitals of the contaminant on the surface are interacting. Coupling of these orbitals in the surface field results in behavior that deviates from the behavior of both materials. The contaminant and the surface can be thought of as a molecular complex. Molecular complexes have different behavior than the sum of the behaviors of the constituents. Copper 2^{+} ion has a light blue color in solution, sodium chloride is colorless, yet when aqueous copper 2^{+} is mixed with an excess of sodium chloride, tetrachloro copper 2^{-} is formed which is green. The chemical and physical properties beyond the color are affected significantly as well. The coupled behavior will necessarily be different than the uncoupled behavior. This coupled behavior is what must be evaluated for its interactions with the laser radiation.

The outgassing of materials and contaminants in the laser system, is controlled by the interactions of the outgassing material and the materials within or upon which it is located. This interaction is dependent upon the temperatures within the laser system. The overall outgassing rate behavior versus time and temperature can be evaluated, and it should be. This rate determines the rate and effect of the transport of contamination within the system and the rate of cleanliness degradation. There are concentration and transport phenomena that affect the kinetics of the material transport that will be temperature related and dynamic with respect to time.

Material Laser Interaction:

The behavior of a material chemically and physically is largely controlled by the electronic distribution. The interaction of light with matter (up to about 10^{20} volts/meter) is largely a function of the immediate time-dependent local field. This immediate time-dependent local field defines the multipole moments, transition probabilities, and the perturbation of the material that will result in the breakdown of the matter.

Induced polarization or perturbation of molecules generally results in broadening the absorption band energies in the combined system. The interaction of the adsorbed species and the adsorbing surface will lower the energy of the combination. This energy lowering results in an increased excited state lifetime, allowing more time for other paths of energy release, such as molecular interconversion (chemistry) or breakdown.

The high energy of the clean surfaces within a system, especially in the presence of radiation, raises the energy of the surfaces. This increased surface energy will subsequently increase the potential energy release upon adsorption of materials. Therefore, in cases where clean surfaces are present in the radiation field of the laser beam and its scattering, there will be a greater driving force for contamination than in areas that are not as clean or as exposed to radiative energy. Thus, transport mechanisms such as creep and adsorption will be accentuated within the laser field. Additionally, the electric field of the laser can drive the transport of dielectric materials toward the peaks of the electric field and subsequently the peaks of the laser intensity. The same dielectric attraction applies to outgassing materials as well.

The interaction of molecules with the high intensity light in laser systems has spawned the fields of laser spectroscopy. This has allowed the development of of techniques including those capable of single molecule detection. With this level of detectability, the paradigm of a Maxwell-Boltzmann ensemble of molecular energy states and a minimal perturbation of the system by the measuring beam is not valid. Many of these techniques make use of adsorption on an optical surface for increasing the probability of detection, which is equivalent to the adsorption of a contaminant on an optic.[3] This means that the limiting quantity for effect of a contaminant may be as low as one molecule. The damage induction level is probably somewhat higher as contamination induced laser optical damage is not a given in most systems, and contamination concentrations will be greater than one molecule.

Materials Selection:

In the selection of the materials used in the laser system, the optical materials should be selected from the best quality starting materials. These materials should exceed the requirements of the system. The properties will likely degrade or change during the lifetime of the parts. Slight variations in the microscopic properties of the optical materials will result in forces that will degrade the properties over time and laser shots. Materials that are subject to change due to their environment in the system in its operating environment should be avoided. If the properties change, the initial, intermediate and final states must be evaluated for the application.

Optical coatings should be designed for operation within the environment in which they are used. Coatings such as anti-reflection coatings and high reflection coatings will change properties upon transition into a new environment, especially those which are not fully dense. This is typified by silica sol-gel coatings. These coatings change their properties significantly depending upon their degree of hydration. Sol-gel coatings tend to absorb significant amounts of contaminants.

Materials systems that are known to cycle hydration states such as chromium conversion coated aluminum should avoided. These materials will tend to generate particles upon humidity cycling. The rules of thumb for dehydration and destabilization of these materials are within a relatively controlled environment. In a space or purged dry environment the equilibrium will be shifted and the materials will lose the water under lower temperature conditions. Likewise, coatings such as gold are notorious for particle shedding, and for pyrotechnics within laser systems.

Particulates tend to absorb energy until either they evaporate or burn off within high energy laser systems. The diffraction patterns induced in the laser system will propagate causing hot spots and damage throughout the laser. Look hard for well adhering strong coatings that are stable under all of the conditions that they will see. Electro-polished stainless steel is always a good starting point.

Radiation testing of all parts or witness pieces should be tested in a radiation environment more rigorous than would be expected in operation. Point defects induced by radiation result in microscopic changes in the properties which are amplified greatly in rapidly changing fields. In certain circumstances, there may be self-healing of the radiation induced defects (annealing), this is more likely to occur during testing than in operation. Radiation testing of optical components should as a result test for optical changes at laser radiation levels consistent with those seen in laser operation. Testing the laser system operation in full operational configuration at higher than normal radiation levels is likely the best test configuration.

Outgassing of materials is a serious issue in the selection of materials. The selection of polymerics and materials with porosity should always be tempered with actual testing of the materials received. Using ASTM E-595 data alone for acceptance of a material is a poor choice. This test was designed for the evaluation of material physical property loss upon autoclaving. This test was never designed for the evaluation of contamination potential of a material. Many of the materials that are considered excellent in this test are among the worst contamination risks in laser systems. Test every material, identify its outgassing components, evaluate the outgassing components, and avoid those such as silicone, aromatics, and other materials that are known or suspected to be bad actors.

Physical properties behavior is another issue to keep in mind. Silicate based glasses and fused silica are known to degrade in the presence of stress and moisture. The grinding of optic edges for additional bond strength increases the potential for contamination for both particulates and molecular contamination. The bond strength for optics in most well designed optic mounts do not require the roughening of the optic surface. Press fit of component parts within a thermally cycling system, especially if there are differences in either the thermal conductivity of coefficient of thermal expansion should be avoided. This type of mounting will result in the parts walking or excessive stress being applied to the part, resulting in unwanted optical behavior.

Contamination Specification:

The original estimation of a survivable contamination level for a laser optic system is mostly guesswork at this time. Since the inception of laser systems it has been known that contamination decreases the laser induced damage thresholds of optics. There has been significant effort invested in attempting to define the inter-relation of laser parameters and optic damage. There is little consensus on the relationships of laser beam properties and laser optic damage. The issue of contamination, either particulate or molecular, raises a general consensus that little is known, and that it is bad. There are a few guide posts that provide some direction, but nothing quantitative, and nothing that allows the inter-relation of the data.

The route to the selection of a contamination level is left to a guess or using someone else's numbers. For high reliability systems, a value of a few micrograms per square centimeter or less is typically chosen, based upon numbers from Lawrence Livermore National Laboratories or elsewhere. There is no good guide to whether this will be sufficient in a specific system or not. The use of such a general specification is artificial at best as all particles are treated the same and all molecular species are treated the same, which they obviously are not.

Measurement and evaluation of materials that outgas from the hardware before, during and after build is a critical part of identification of the contamination effects within a laser. Identification of the existing contamination level within the system is critical. Whether the laser system survives or not, if the contamination environment within the laser is identified, something can be learned. This also requires a description of the optical surfaces and locations within the system, and the beam properties as well. It is unreasonable in the build of a special purpose high intensity laser not to pay strict attention to the laser build environment. This is especially true for the materials, people, procedures, and environment in which the laser is built. The laser build environment can have much greater effect upon the cleanliness of a system than the materials themselves. Continuous monitoring of the build environment is mandatory. Contamination is dynamic and must be treated as such.

Measurement of the cleanliness of the laser should involve the cleanliness of the materials and parts from the final machining operations, through subassembly level to the final assembly level. There is significantly less risk involved in cleaning individual parts than in cleaning the final assembled laser. Verification of the testing protocols is requisite. Sampling a surface without verification of the sampling technique is not meaningful. Likewise, baking out of a piece of hardware without verification of the outgassing rate is also not meaningful. No detectable amount of material, or no signal from a detector is not a useful value. A lack of signal means that the signal is below the detection limit for the instrument, or the instrument is not operating correctly. Without a valid measurement, you do not have a valid measurement. Having access to one or more people that are intimately familiar with contamination, trace measurement techniques, materials, chemistry and have a working knowledge of lasers and laser damage is invaluable.

Maintaining the cleanliness of the laser is often more difficult than getting it clean in the first place. Cleaning a part and then storing it in a manner that allows recontamination entails potentially more risk than not cleaning it in the first place. It should be requisite that the storage conditions be monitored as well. As the parts are processed, documentation of the state of the parts as they are processed should be carried out as well. If a coated optic begins shedding particles of coating after receipt, this should be documented. This requires incoming inspection, inspection after cleaning, inspection during build up of sub assemblies, and inspection prior to final assembly, with reference back to the incoming inspection. This requires tracking of each part individually.

Conclusions:

In any laser system, there is a required lifetime. In the evaluation of the contamination status of a system, particular emphasis should be paid to assuring that the required cleanliness level be maintained to end of life. This requires a number of assumptions, and many more measurements. The more meaningful measurements made on the system, the fewer assumptions that will have to be made.

Things to consider are the degradation of materials, outgassing rates, and thermal behavior within the system.

Measuring and identifying outgassing species and their rates is a good start. Assuming that any material that outgasses will impinge on an optic and remain there is likewise a good assumption. There is strong evidence that even monolayer levels of molecular contamination will cause damage. In fact, there is reason to believe that that monolayer levels of contamination may represent the greatest threat to high intensity laser systems.

Documenting the stability or instability of all of the components within the laser, based upon appearance is a good starting place for assuring that the components of the system will not begin shedding particles. Carrying out tape lift sampling of surfaces outside of the beam will provide invaluable information for all future laser builds.

Designing laser systems with routes to determine the performance of the internal components of the laser, while not improving the reliability of the built unit, will allow risk management of subsequent builds. Minimally, measuring pump diode output, thermal rise of components, heater power, etc can provide great direction in mitigating risk to other laser systems.

It is also requisite that there be a good understanding of the contaminants and the internal environment of the laser. Without the understanding of the physics and the chemistry of the contaminants within the laser environment, understanding of the behavior of the laser can not be achieved. Without understanding of the behavior the risks can not be managed.

References:

1. Stone, A.J.,The Theory of Intermolecular Forces, International Series of Monographs on Chemistry 32, Oxford University Press, Oxford, 1996.
2. Adamson, A. W., Physical Chemistry of Surfaces, Interscience Publishers, New York, 1960.
3. Kang, S.H., M. R. Shortreed, E.S. Yeung, “Real-time Dynamics of Single-DNA Molecules Undergoing Adsorption and Desorption at Liquid-Solid Interfaces,” Anal. Chem. 73, p1091, 2001.